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A Low-Impedance, Skin-Grabbing, and Gel-Free EEG Electrode*

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Abstract— **Inspired by the extraordinary object grabbing ability of certain insects (e.g., a grasshopper), we have developed a novel dry EEG electrode, called the skin screw electrode. Unlike the traditional disc electrode which requires several minutes to install, the installation of the skin screw electrode can be completed within seconds since no skin preparation and electrolyte application are required. Despite the drastic improvement in the installation time, our experiments have demonstrated that the skin screw electrode has a similar impedance value to that of the disc electrode. The skin screw electrode has a wide range of applications, such as clinical EEG diagnosis, epilepsy monitoring, emergency medicine, and home-based human-computer interface.**

I. INTRODUCTION

The electroencephalography (EEG) provides a unique window to observe the functional activity within the brain and has been a major diagnostic tool for a variety of neurological diseases [1-4]. For example, in the study of epilepsy, EEG is extremely useful in observing spikes and other epileptiform discharges from the brain. It is also essential in distinguishing among nonconvulsive status epilepticus and other diseases with similar symptoms [4-6]. In recent years, the EEG has become the most popular method for establishing non-invasive Brain-Computer Interface (BCI) which provides an information link between the brain and an external computer[7,8]. Furthermore, in clinical practice, rapid diagnosis of acute neurological diseases is highly important. For example, if an acute stroke is diagnosed quickly and correctly, the administration of tissue Plasminogen Activator (tPA) can significantly improve prognosis [9-11]. Since rapid diagnosis and timely treatment will be greatly beneficial to patients, the development of an EEG electrode that can be installed quickly on the scalp is highly significant in emergency medicine [12].

Despite the popular utilization of EEG, the standard procedures for EEG placement are time-consuming and tedious. They are also uncomfortable and sometimes painful for patients because of the requirement to remove the stratum corneum which is the top protective layer of the skin. During the EEG electrode installation, scalp hair hinders electrode contact to the skin, requiring the electrode to be glued to the scalp using a tape or collodion. In addition, body heat constantly evaporates the moisture in electrolytic gel, which increases the electrode impedance over time. Furthermore, body motion (e.g. during patient transport or epileptic seizure), snagging of the wire leads and deterioration of the adhesive often cause electrodes to fall off. It is highly desirable to have a convenient EEG electrode that can be attached to the scalp of the patient quickly and reliably. Therefore, dry electrodes, which require no skin preparation and no gel, have been developed [13-20]. However, one major problem with the existing dry electrodes is the high skin-electrode impedance. To reduce the impedance, micro machining techniques have been applied to create a needle-like substrate for the electrode to penetrate the outer layer of the skin [16-20]. However, the dry electrode often produces EEG data of low quality; the manufacturing of such an electrode is complex; it is still inconvenient to install the dry electrode on the hairy scalp; and in most cases, the electrode has to be affixed using a supportive mechanism, such as a headband, a helmet, or an adhesive tape.

Inspired by the extraordinary grabbing ability of certain insets, such as the grasshopper, we have designed a biomimetic EEG electrode, called the skin screw electrode, that can grab skin by slightly twisting and pressing [1]. The tooth-like structure of our electrode mimics the legs of grasshopper. In this paper, we first present the design and implementation of our skin screw electrode. Then, we demonstrate our experimental results which validate the performance of this new electrode.

II. DESIGN AND IMPLEMENTATION

A. Structure Design

The basic design of the skin screw electrode, made of gold-plated stainless steel, has a cylindrical shape, approximately one centimeter in diameter and one centimeter in height (Fig.1(a)). This electrode can be easily installed on a person's scalp (Figs.1(b)&1(c)). Numerous micro teeth, shown in Fig. 1(d), are aligned on the bottom rim of the electrode. The teeth are in a 2^o - 5^o angle to the plane of the bottom rim. When the electrode is twisted slightly in the direction as shown in Fig. 1(b), these teeth hook on the painless, but mechanically extremely strong stratum corneum (the very top layer of the skin) and make electrical contacts without the need of applying electrolyte (Fig. 1(c)). During this process, the hairs are pressed into the space between these micro teeth. The skin screw electrode can be securely attached to the scalp in approximately one second. Since the penetration depth of the electrode teeth is just enough to overcome the high electrical resistance of the top layer of epidermis, during electrode installation, the subject usually feels only a slight pressure at the site of the scalp instead of pain. A magnetic sphere is used to connect the electrode and the electrode lead so that electrodes can be easily attached or separated from the leads. This connection mechanism not

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only provides convenience to patients, but also prevents pulling the electrode off the skin when the electrode lead is accidentally pulled in force [1].

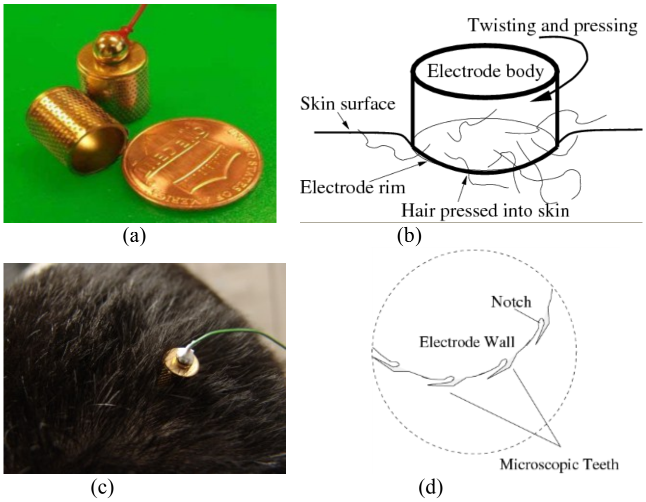


Fig. 1 (a) Electrode prototype; (b) application of the skin screw electrode; (c) an electrode installed on a person's head; (d) amplified view of bottom rim of the electrode.

B. Implementation of Skin Screw Electrode

The construction of the complex shaped tiny electrode teeth (see Fig. 1(d)) represents a technical challenge. After several years of exploration, we have found a simple and cost-effective way to manufacture the electrode teeth using photolithography which has been utilized widely in the semiconductor industry [1]. Micro tooth patterns of hundreds of electrodes are created on a single sheet of stainless steel whose thickness is approximately 0.1mm (Fig. 2(a)). In this process, light is used to transfer electrode patterns from a photo mask to a light-sensitive chemical applied to the metal sheet. After a protection film is formed in the desired portions of the sheet, a series of chemical etching is utilized to form the microscopic teeth simultaneously. The structure of a single strip is shown in Fig. 2(b). The material of the sheet and its thickness determine the hardness of the teeth. Next, each strip is peeled from the sheet and rolled precisely as shown in Fig. 2(c). Then, the ring of the electrode is formed. Finally, gold or another material is electrochemically plated or sputter-coated on the electrode to reduce the skin-electrode impedance (Fig. 1(a)). Using this procedure, mass production of the electrode becomes feasible and the cost of manufacturing the skin screw electrode decreases significantly, estimated to be around 20 U.S. cents when mass-produced. At this low cost,

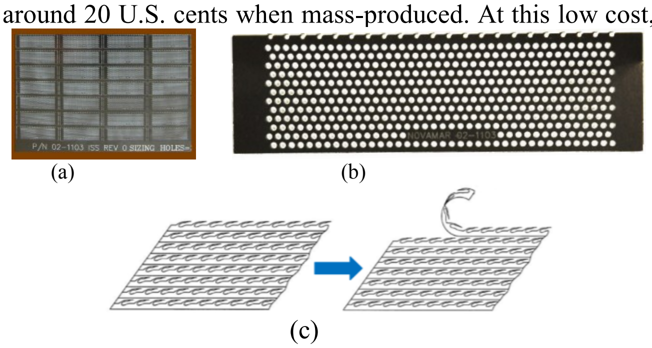


Fig. 2 (a) Stainless steel sheet containing strips for twenty-eight electrodes with micro teeth; (b) structure of a single strip; (c)schematic diagram to roll each strip into an electrode.

the skin screw electrode may be used only once (disposable) although multiple uses (after proper sterilization) will not degrade performance if the micro teeth are not deformed significantly.

III. Performance Comparison to Disc Electrode

Because the disc electrode is one of the most commonly used, most high-performing scalp EEG electrodes, we utilized this electrode for performance comparison. Two experiments have been conducted to compare both the impedance and the acquired EEG data obtained from these two types of electrodes.

A. Impedance Measurement

With an Institutional Review Board (IRB) approval, we compared electrode impedances using an impedance meter on four healthy human subjects. 80 impedance measures (40 each for the skin screw electrodes and the disc electrodes) were made during this experiment. Skin screw electrodes were applied manually on unprepared scalp with normal hair types and styles. A gold coated disc electrode was placed on the forehead as the ground electrode. The standard procedure was utilized for the disc electrode, including scalp preparation, electrode taping, and post-experiment scalp cleaning. The disc electrodes (Grass Technologies, West Warwick, RI) used in our experiments were gold plated with a diameter of 10mm. The impedance between the electrode and the ground was meeasured using a clinical EEG electrode impedance meter (Model EZM5, Grass Technologies, West Warwick, RI) with the measurement frequency of 30Hz. The impedance comparison result is shown in Fig. 3. A Student t-test (α=0.05) indicates no significant difference in impedance between the two types of electrodes.

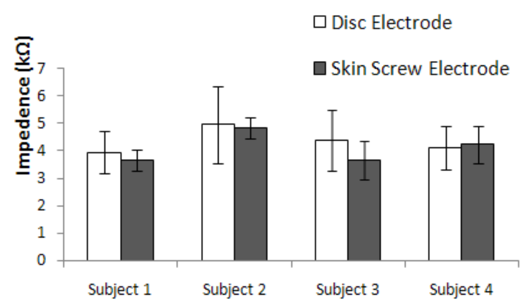


Fig. 3 Impedance comparison between skin screw electrode (black bars) and standard disc electrode (white bars).

B. Spontaneous and Evoked EEG Measurements

In this experiment, eight pairs of electrodes (skin screw electrode, commercial disc electrode) were installed side-by-side closely in the frontal, central, temporal and occipital regions (i.e., F3&F4, C3&C4, T5&T6, O1&O2) of the subject's scalp. Standard scalp preparation was utilized for the commercial disc electrode performed by an experienced EEG technologist while no preparation used for the skin screw electrodes. A disc electrode was placed on the forehead as the ground. The sampling rate was set to be 300Hz. All the electrodes were connected to the same EEG recording system (NeuroNet VI, Computational Diagnostics, Inc., Pittsburgh, PA) as different channels, see Fig.4.

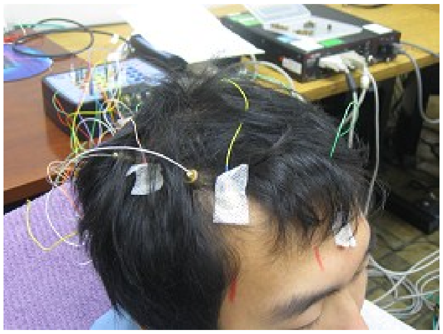
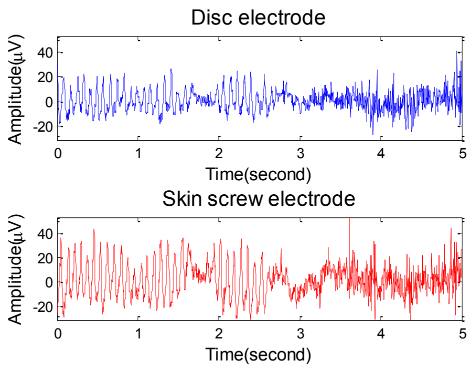
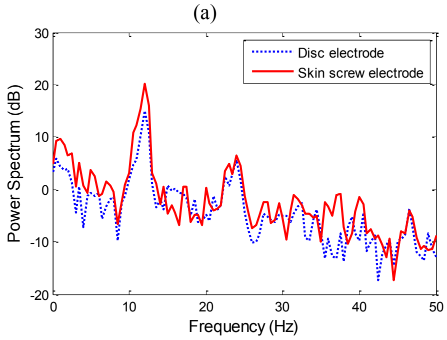


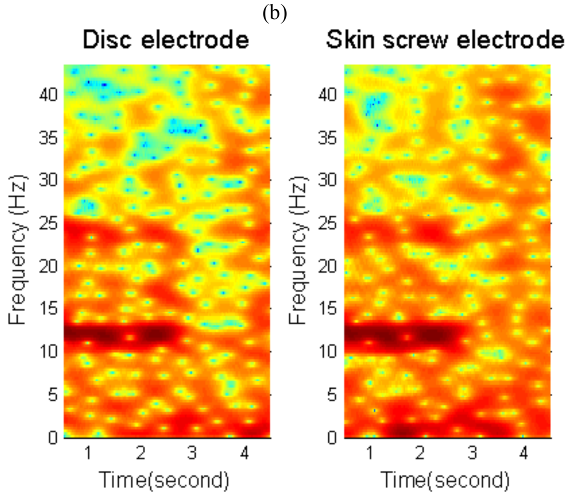
Fig. 4 Experiment setup to compare skin screw electrode with disc electrode using a commercial EEG recording system.



(a)



(b)



(c) (d)

Fig. 5 (a) Raw EEGs acquired by the commercial disc electrode (top panel) and the skin screw electrode (bottom panel); (b) their spectra estimated using Welch method (dash curve - disc electrode, solid curve - skin screw electrode); (c) spectrogram of the data from disc electrode; (d) spectrogram of the data from skin screw electrode.

The subject was asked to relax while EEG data are acquired with eyes open and closed (about 2 minutes each). Fig. 5(a) illustrates two segments of differential EEG signals between site T5 and O1 recorded by disc electrode and skin screw electrode. The first part of the signals shows significant alpha waves (around 11Hz), which are known indicators when subject's eyes are closed. The two EEG segments were also compared with respect to the power spectra and the time-frequency distribution (calculated by the Short-Time Fourier Transform (STFT)). The analysis results in Figs. 5(b), 5(c) and 5(d) indicate that the EEG signal recorded by the skin screw electrode is comparable to that recorded by the disc electrode.

We also acquired somatosensory evoked potentials (SSEPs) from all human subjects using a similar experimental setup. The sampling rate of the EEG recording system was set to be 3000Hz and the reference electrode was Fz. For each subject. The left median nerve at the wrist was stimulated electrically at a frequency of 3.43Hz and the EEG was averaged synchronously with respect to the locations of stimuli over 256 trials. Four SSEPs were acquired for each subject. Fig. 6 shows the SSEPs recorded by disc electrode and skin screw electrode on one subject. Because each pair of electrodes was placed about 2cm apart, the amplitudes and the waveforms of the two EEG signals are not exact the same. From Fig.6, it can be seen the negative peaks at 20ms are very significant and consistent in all SSEPs.

IV. Performance Comparison to Needle Electrode

We also conducted an experiment to compare our skin screw electrode with the needle electrode. Two skin screw electrodes and two needle electrodes were placed in the frontal and central area, and one disc electrode was placed on the forehead as the ground (Fig. 7(a)). The needle electrode was installed by an experienced EEG technologist following the routine procedure. Then, the skin screw electrode was installed closely. The signals were recorded by the same NeuroNet VI EEG recording system as described previously. A segment of the acquired differential EEG signals between each pair of electrodes and the corresponding power spectra are shown in Fig. 7 (b) and (c), respectively. Our results indicated no significant differences between these two signals.

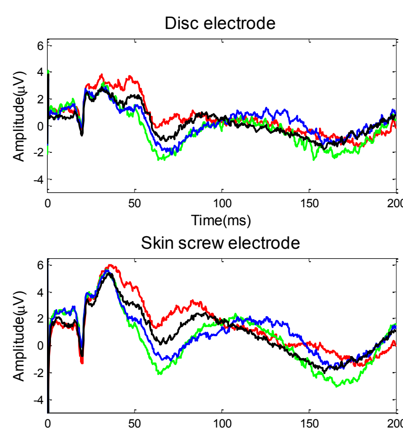
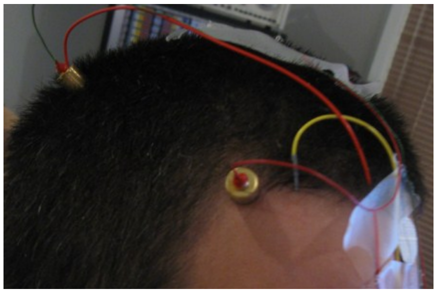
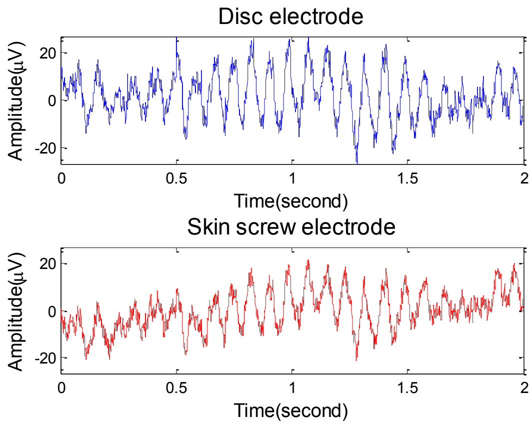


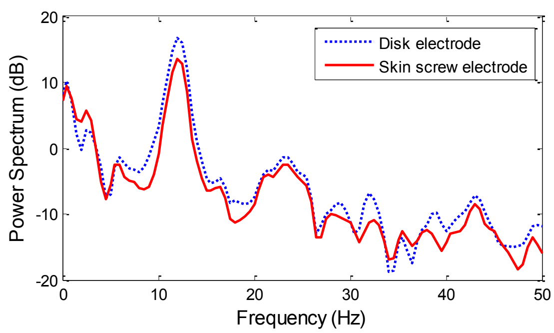
Fig. 6 SSEP signals acquired by the commercial disc electrode (top panel) and the skin screw electrode (bottom panel) in central region (C4-Fz). Each colored line represents one SSEP.



(a)



(b)



(c)

Fig. 7 (a) Experiment setup; (b) EEG acquired by the commercial needle electrode and the skin screw electrode; (c) spectra comparison (dash curve - disc electrode, solid curve - skin screw electrode).

V. Conclusions

It has been a common concept that wet EEG electrodes produce better performance, but are complex to install than dry electrodes. This traditional concept has now been challenged by our development of the skin screw electrode which is both high-performance and easy to install. By pressing and twisting the new electrode clockwise, it hooks the scalp firmly at the designated site. Such a skin attachment has an extraordinary strength, yet is very easy to detach by slightly unscrewing. Our comparisons between the new skin screw electrode and the commercial disc electrodes have demonstrated that: 1) the new electrode has an impedance comparable to the disc electrode; 2) the new electrode provides equal EEG data quality; and 3) the skin screw electrode significantly over-performs the disc electrode in installation time and stability.

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